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Development of a general sustainability indicator for renewable energy systems: A review

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ABSTRACT

Renewable energy is considered as a solution for mitigating climate change and environmental pollution; however, an important problem of the application of renewable energy systems (RESs) is that the evaluation of the sustainability of these systems is extremely complex. In order to assess the sustainability of renewable energy systems comprehensively, the use of sustainability indicators (SIs) is often necessary. Since sustainability indicators are necessary to reflect various aspects of sustainability, the development of a general sustainability indicator (GSI) including many basic sustainability indicators (BSIs) becomes critical. In this paper, the methods of selection, quantification, evaluation and weighting of the basic indicators as well as the methods of GSI aggregation are reviewed. The advantages and disadvantages of each method are discussed. Based on these discussion and the analysis of the uncertainties of sustainability assessment, an effective framework and its procedures of the development of GSI for renewable energy systems is presented. This GSI is not only able to evaluate all the sustainability criteria of RESs, but also can provide numerical results of sustainability assessment for different objective systems. The proposed framework in this study can be used as a guidance of the development of sustainability indicator for various renewable energy systems.

Contents

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1. Introduction

In recent years, an increasing number of renewable energy sources such as geothermal, solar, wind, combustible renewables and waste are used over the world, because of their advantages of less emission, less pollution, clean and less fossil fuel resources usage. In order to guide future investment of a renewable energy source based system, the sustainability of the system should be assessed for decision-making; however, there is no common tool available to evaluate all the aspects of sustainability. For example, cost is only used to reflect the aspect of economic sustainability, but it is incapable of evaluating the system quality of other sustainability criteria like environmental and social considerations.

This paper aims to propose a development framework of a general sustainability indicator (GSI) for RESs through reviewing and comparing the different ways of indicator selection and indicator modeling strategy. This GSI is a tool of sustainability measurement reflecting all the criteria of sustainability assessment including economical, environmental and social criteria. Through investigating the disadvantages of the development methodology of existing sustainability indicators, the fuzzy analytical hierarchy processing (FAHP) and fuzzy comprehensive evaluation (FCE) methods are employed to aggregate all the selected basic indicators and criteria into the general indicator.

2. Concepts of sustainability indicator

Sustainability indicator for RESs is developed to measure sustainability reliably. The main objective of SI is to provide a comprehensive and highly scalable information-driven architecture of sustainability assessment [1]. Most existing SIs are quantitative, so that it is understandable who is considering of a renewable energy system's sustainability and who will help them to make a decision on the investment [2]. A few basic types of SIs can be distinguished by their methods of construction and level of aggregation [1], as outlined below:

- Indicator: This includes results from the processing (to various extents) and interpretation of primary data.
- Aggregated indicator: This combines, usually by an additive aggregation method, a number of components (data or sub-indicators) defined in the same units.
- Composite indicator: This combines various aspects of a given phenomenon, based on a sometimes complex concept, into a single number with a common unit.
- Index: This generally takes the form of a single dimensionless number. Indices mostly require the transformation of data measured in different units to produce a single number.

The GSI of this study is the fourth type (index), because it has to reflect all the aspects of the sustainability quality of a whole renewable energy system, as well as the interaction of its subsystems and/or components [3] and, more importantly, all the quality parameters have different units. As a result, the main challenge of SI development is to assess the various criteria of sustainability, and if a single criterion is used to assess the system's sustainability it does not work any more. An example is taken to present this issue. The mean cost of electricity generation of solar PV (photovoltaic) and wind energy is respectively up to 0.24 and 0.07$/kWh, while the conventional coal electricity generation just costs 0.048$/kWh. This means that coal electricity is better than solar and wind economically, but this does not mean that coal is better than the other two energies when seen from other points of view.

As discussed above, the hierarchy of this GSI has to have three levels as shown in Fig. 1. The top level is called the general sustainability indicator (GSI) [4–6]. This level gives a numerical evaluation of the sustainability. The second level is the criteria (C_i) level. This level generally includes a few assessment criteria of

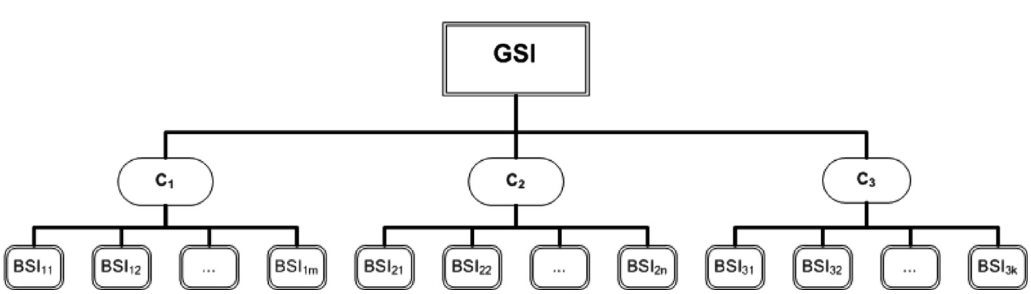

Fig. 1. The hierarch of GSI.

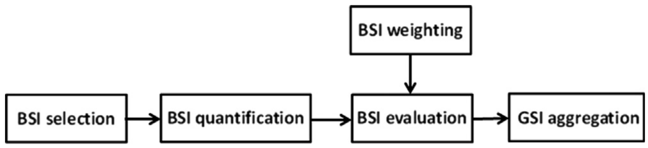

Fig. 2. The development strategies of GSI.

sustainability, such as economical, environmental and social. The third level is called basic sustainability indicators (BSI_{ij}) [7] which are chosen based on the selected criteria.

The processes of the indicator development are shown in Fig. 2. The five main strategies are

(A) BSIs selection: BSIs selection is to select some basic indicators which reflect the sustainable quality of RESs based on some selected sustainability assessment criteria.
(B) BSIs quantification: Because the selected BSIs have different dimensions, it is necessary to quantify them as the non-dimension variable with the value between [0, 1].
(C) BSIs evaluation: BSIs evaluation is to evaluate the selected BSIs by individual assessment criterion.
(D) BSIs weighting: This step is to calculate the weight of each BSI affecting the GSI.
(E) GSI aggregation: This strategy is to obtain the final GSI value by aggregating all the BSIs evaluation.

For the BSIs selection, the sustainability assessment criteria are reviewed. The sustainability assessment criteria and scales are discussed for the BSIs selection, quantification and evaluation. Moreover, the modeling methods are discussed for the BSIs weighting and GSI aggregation.

3. Sustainability assessment criteria and scales

It is not absolute that more indicators are helpful to the sustainability assessment. It requires caution so that the criteria selection covers all the aspects of sustainability and does not overlap with each other too much [8]. Generally, the indicator selection should obey the following principles [3,9]:

- Reflect sustainability concept.
- Measure quality corresponding to specific sustainability goals.
- Be based on timely information.
- Be based on reliable information.
- Reflect a strategic view
- Supply references on systems optimization.
- Reflects longevity of system design.

3.1. Sustainability assessment criteria selection

A number of different sustainability assessment criteria were used in the previous studies of sustainability indicator development for RESs. As shown in Table 1, in the literatures [3,4,7,8,10–13] which clearly project a SI concept for RES, economic, environmental, social and technological criteria were popularly used in SI development; however, the different researches have different selection criteria which have a different significance for the multi-criteria quality evaluation of RESs for different engineering purposes. The scales which have more degrees are able to provide more precise but are more difficult to work out.

Approaching the sustainable development concept, the most popular criteria selection of SI development of RESs would be based on practical terms of sustainable development. Elkington [14] coined the Triple Bottom Lines (TBL) method to explain sustainability. As shown in Fig. 3, TBL of sustainable development should capture an expanded spectrum of values and criteria for measuring organizational success: social development, environmental protection and economic growth. A successful assessment of RESs should evaluate all the performances in economic, environmental and social aspects.

Table 1
Different criteria sets of sustainability indicator.

Criteria	Number of criteria	Literatures
Resource quality, economic quality, environment quality, technological quality and social quality	5	[10]
Economic, institution, ecology, sociology and technology	5	[11]
Performance, market, environment and social indicators	4	[4]
Resource, environment, social and economic	4	[3,12]
Ecosystem and human system	2	[7,8,13]

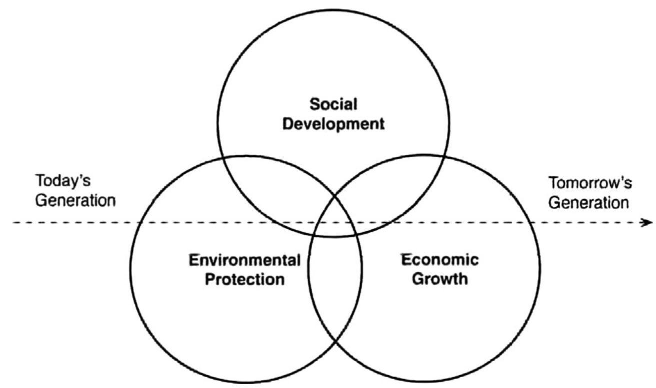

Fig. 3. The dimensions and interactive process in sustainability [102].

Table 2
Sustainability indicator scale.

Number of sustainability degrees	Literatures
2 sustainable degrees	[1,15]
3 sustainable degrees	[8,13,17,103–107]
5 sustainable degrees	[13,17,108,109]
9 sustainable degrees	[8,13,17,104,105]
Continuous sustainability degrees	[3,16]

3.2. Sustainability scale

Sustainability scale is the set of judgement of sustainability degree; the more the scales of indicator, the greater the precision. Table 2 shows different sustainability scales in previous related SI. The earliest, simplest and vaguest scale has only two judgements of sustainability: strong and weak [1,15]. After that, there were sustainability scales including 3, 5 and 9 degrees of BSIs or GSIs for RESs' sustainability assessment. In addition, some SIs [3,16] have no linguistic judgement on sustainability degree but have continuous numerical value of sustainability generally in the interval [0, 1]. In a same SI development, BSIs and GSI sometimes have different scale. For example, in some literatures [13,17], the BSIs are 3-degree sustainability scale but GSI is 9-degree scale.

3.3. Methods of BSIs quantification

A basic principle of indicators' selection is that all the indicators must be 'measurable' [18]. Also, the indicators require to be transferred into data [4]. Generally, the measured values of the selected indicators are of two types. One is the type that can be accurately measured as a numerical value. For example, the amount of money is used to represent the cost of a RES, and the amount of ton/year is used to represent the CO_2 emissions. The other category of indicators is the one which is neither able to measure its value, nor it is able to determine the degree of sustainability in spite of the numerical value being known. For example, even if it is known that one RES has 100 ton/year of CO_2 emissions, the sustainability degree of the CO_2 emissions indicator is difficult to define. In general, normalization is used to deal with this gap.

3.3.1. Normalization

There are three popular methods of BSIs normalization in SI development. They are life cycle assessment (LCA) normalization method [19], Phillis' fuzzy measure normalization method [8] and Afgan's specific quality normalization method [20].

In the handbook of LCA referring to the ISO 14000, it is written that normalization is regarded as a strongly recommended step for any LCA [19]. The normalization process is given by

$$BSI_{i,\ nor} = \frac{BSI_i}{BSI_{i,\ ref}} \tag{1}$$

where $BSI_{i,\ nor}$ is the normalized basic sustainability indicator, non-dimension; BSI_i represents the i-th category basic sustainability indicator; $BSI_{i,\ ref}$ represents the reference indicator value of the i-th category basic sustainability indicator.

In the Phillis' book of *Fuzzy Measurement of Sustainability*, a normalization method is summarized to unify the basic indicators with a variety of scales and units [8]. Three linear interpolation equations are given for the three types of indicators: smaller is better (Eq. (2)), larger is better (Eq. (3)) and closer to the desired values x_j^* is better (Eq. (4)):

$$x_c = \begin{cases} 1, & z_c \le T_c \\ \dfrac{U_c - z_c}{U_c - T_c}, & T_c < z_c < U_c \\ 0, & z_c \ge U_c \end{cases} \tag{2}$$

$$x_c = \begin{cases} 0, & z_c \le \nu_c \\ \dfrac{z_c - \nu_c}{\tau_c - \nu_c}, & \nu_c < x_c < \tau_c \\ 1, & z_c \ge \tau_c \end{cases} \tag{3}$$

$$x_c = \begin{cases} 0, & z_c \le \nu_c \\ \dfrac{z_c - \nu_c}{\tau_c - \nu_c}, & \nu_c < x_c < \tau_c \\ 1, & \tau_c \le z_c \le T_c \\ \dfrac{U_c - z_c}{U_c - T_c}, & T_c < z_c < U_c \\ 1, & z_c \ge \tau_c \end{cases} \tag{4}$$

where ν_c, τ_c, T_c and U_c are coefficients of BSIs; z_c is the original values of BSIs. and x_c is the normalized values of BSIs. Their desired values are dependent on the specific indicators and the determination form is shown in reference [8].

The normalization method given by Eq. (4) is based on two typical extreme systems: the weakest sustainable system and the strongest sustainable system. In addition, the normalization method is also given by [5,10,20,21]

$$q_i(z_i) = \begin{cases} 1, & z_i \le \min(i) \\ \left(\dfrac{\max(i) z_i - z_i}{\max(i) - \min(i)}\right)^{\lambda}, & \min(i) < z_i \le \max(i) \\ 0, & z_i < \max(i) \end{cases} \tag{5}$$

where $\min(i)$ and $\max(i)$ are the minimum and maximum value of different systems for given indicator respectively; λ is the exponent's value which depends on the experiences of indicator users.

4. Modeling of multi criteria sustainability indicators

4.1. Methods of BSIs weighting

There must be a number of BSIs for each GSI, and therefore it is necessary to rank their importance before aggregating them. In order to obtain a numerical value of sustainability, the importance of BSIs should be quantified as well. Consequently, the weight of each indicator is needed. The previous weighting methods are introduced as below.

4.1.1. Equal weighting method

The weights of all the BSIs are equal to others. The weights of BSIs in the equal weighting method can be defined by

$$w_i = \frac{1}{n}, \quad i = 1, 2, 3, \ldots, n. \tag{6}$$

The method was popular in some sustainability indicator development and multi-criteria decision making of energy system [4,22–26]. The vital shortcoming of equal weighting method is that this method is impossible to reflect the different importances of various BSIs and different criteria, and this method would not be accepted in the development methodology of modern SI.

4.1.2. Analytical hierarchy process (AHP)

The AHP method determines the relative importance values of each pair of indicators [27] in which values represent the relative preference of each pair-wise comparison. After constructing the matrix of preferences, the weights can be calculated in some methods, such as geometric mean method (GMM) [28] and maximum eigenvalue vector method (MEVM) [29]. In order to validate the reliability of the AHP model, a consistency ratio is used to measure the consistency of the comparison matrix.

For calculating the consistency index (CI), the deviation from consistency is given by [29]

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{7}$$

where λ_{max} is the maximum eigenvalue of the comparison matrix; and n is the number of indicators. Then, consistency ratio (CR) is computed to estimate the consistency of pair-wise comparisons by

$$CR = \frac{CI}{RI} \tag{8}$$

where the determination of RI (Random Consistency Index) is based on Table 3 [30].

There are, however, five major shortcomings of AHP [31] which present obstacles for AHP to be used as BSIs weighting: (1) the

Table 3
Random Consistency Index values.

Number of BSIs	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

AHP method is mainly used in nearly crisp decision applications; (2) the AHP method creates and deals with an unbalanced scale of judgment; (3) the AHP method does not take into account the uncertainties associated with the mapping of one's judgment to a number; (4) ranking of the AHP method is rather imprecise; (5) the subjective judgment, selection and preference of decision-makers have great influence on the AHP results.

4.2. Methods of GSI aggregation

For verifying the creditability of the developed sustainability indicator by multi-criteria decision-making and obtaining a final numerical result of sustainability indicator, the indicators must be aggregated into a GSI [18].

4.2.1. Weighted arithmetic average

The weighted arithmetic mean (WAM) method is used to aggregate BSIs into the GSI [3,4,10,23,32]. A linear agglomeration function is given by [3]

$$Q(q;w)=\sum_{i=1}^{m} w_i q_i \tag{9}$$

where q_i is the value of the i-th BSI, and w_i is the weight of the i-th BSI.

4.2.2. Weighted geometric average

In the process of indicator development for comprehensive evaluation problem, the weighted geometric average (WGA) method is also used frequently. This method is also called as non-linear model given by

$$Q(q;w)=\prod_{i=1}^{m} q_i^{w_i} \tag{10}$$

4.2.3. Exponential weighted mean function

The exponential weighted mean function was also used [33]:

$$Q(q;w)=\left(\sum_{i=1}^{m} w_i q_i^{\lambda}\right)^{1/\lambda} \tag{11}$$

In this method, when $\lambda=1$, the function transforms into the WAM method as shown in Eq. (9).

4.2.4. TOPSIS

The TOPSIS (Technique for Order Preference by Similarity to Ideal Situation) [34] is also introduced as an aggregation method. The indicator result is given by Eq. (12). This method is used to compute with words to assess the sustainability of RES [35,36]:

$$Q(q;w)=\sum_{i=1}^{m} w_i (q_i-q_i^*)^2 \tag{12}$$

where q_i^* is an standard value of the i-th BSI.

4.2.5. Fuzzy inference system method

The applications of fuzzy inference system (FIS) in sustainability indicator development are seen in Phillis' articles [7,13,37,38]. The index value OSUS (overall sustainability) for each pair of ECOS (ecological system) and HUMS (human system) is given by [7]

$$\mathrm{OSUS}=a\mathrm{ECOS}+b\mathrm{HUMS} \tag{13}$$

where a and b represent the relative importance respectively of ECOS and HUMS in the calculation of OSUS [7]. It chooses $a=b=1$ to strike an equal balance between the environmental and the human dimensions of sustainability [7], however, the impacts of the two dimensions on the OSUS value are also determined by the rule base. For example, ECOS has three inputs, namely LAND (land indicator), AIR (air indicator), and WATER (water indicator). The fuzzy set of ECOS is determined from

$$\mathrm{SUM}=\mathrm{LAND}+\mathrm{AIR}+\mathrm{HUMS} \tag{14}$$

Then, the rule base for ECOS is given by Eq. (15) [7]. The similar rule bases are used in different levels of the indicator development:

$$\mathrm{ECOS}=\begin{cases} \mathrm{VB}, & 0\le SUM\le 1 \\ \mathrm{B}, & 2\le SUM\le 4 \\ \mathrm{A}, & 5\le SUM\le 7 \\ \mathrm{G}, & 8\le SUM\le 10 \\ \mathrm{VG}, & 11\le SUM\le 12 \end{cases} \tag{15}$$

More generally, rule base is given by the format shown below [39]:

$$\begin{aligned} &\text{Rule 1: IF condition } \mathrm{C}^1 \text{ THEN restriction } \mathrm{R}^1 \\ &\text{Rule 2: IF condition } \mathrm{C}^2 \text{ THEN restriction } \mathrm{R}^2 \\ &\ldots \\ &\text{Rule } n\text{: IF condition } \mathrm{C}^n \text{ THEN restriction } \mathrm{R}^n \end{aligned}$$

The linguistic connections like 'and', 'or', 'else' are used to connect the conditional, unconditional, and restriction statements respectively. The consequent of rules or output is denoted by the restrictions $\mathrm{R}^1, \mathrm{R}^2, \ldots, \mathrm{R}^n$. Although the rule base does not give the weights of each indicator, the impacts of the BSIs on the final results of GSI are given clearly.

4.2.6. Grey relational analysis method

The grey system theory has been invented for evaluating complex systems with multiple criteria [40]. The theory has been used to deal with the uncertainty in the development of sustainability indicator [41]. As the data flow of the indicator shown in Fig. 4, the original values of BSIs are used as the inputs of the indicator and the output is the final score of the general indicator. The function given in Eq. (16) has been used to describe the relationship between outputs and inputs of sustainability indicator:

$$y=f(BSI_1, BSI_2, \ldots, BSI_m) \tag{16}$$

As discussed in Ref. [41], the expression of the function $f(x_i)$ is unknown; and, only three relationships are clearly known: (1) for positive BSIs, the bigger the value, the bigger the sustainability indicator value; (2) for negative BSIs, the bigger the value, the small the sustainability indicator value; (3) for normal BSIs, the closer to the desired value, the bigger the sustainability indicator value.

In this method, the GSI can be considered as a grey system, and the correlation between the BSIs value and the GSI score is also grey. Going through the grey relational analysis method, the key idea is to calculate the grey coefficient, which reflects the relationship between different BSIs and the relationship between BSIs and the GSI, by

$$\xi_{ij}=\frac{\min_{1\le i\le m}\min_{1\le j\le n}(z_{ij})_{m\times n}+\rho\max_{1\le i\le m}\max_{1\le j\le m}(z_{ij})_{m\times n}}{z_{ij}+\rho\max_{1\le i\le m}\max_{1\le j\le m}(z_{ij})_{m\times n}} \tag{17}$$

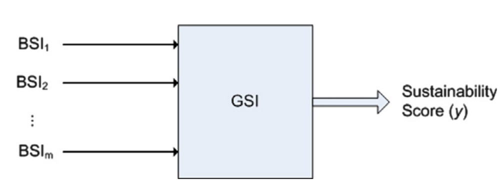

Fig. 4. The information flow of the sustainability indicator [41].

here z_{ij} is obtained by $z_{ij} = |x_{i,opt} - x_{ij}|$, where x_{ij} the normalized indicator value of the j-th evaluated RES for the i-th BSI, and $X_{opt} = \{x_{i,opt}\}$ is the normalized reference sequence.

4.2.7. Others

Some other methods of GSI aggregation have been highlighted in a number of previous studies and other research projects, like Preference Ranking Organization METhod for Enrichment Evaluation (PROMETHEE) [42–44] and Elimination Et Choice Translating REality (ELECTRE) [45–47], or the combination [48–54] of fuzzy methodology with the MCDM (Multi-Criteria Decision-Making) methods discussed above.

4.2.8. Shortcomings and challenges of GSI aggregation

General sustainability indicators must give the numerical value of the sustainability result and the results of all the dimensions of sustainability of the evaluated system, so that the users are able to compare systems sustainability and to select the highest sustainability with the lowest costs (including economic, environmental costs and resources). The users must determine if the benefit of an RES system exceeds its costs and if it is more attractive than other systems. Obviously, a numerical value is helpful for simplifying their assessment and decision making.

When systems performance information are transferred into indicator data, there are three main problems which the previous SI modelings mentioned above are difficult to solve:

(1) The degree of sustainability is fuzzy which cannot be described by crisp number value. When people assess sustainability, there is fuzziness between different sustainability degrees. For example, in the 2-point sustainability scale, it is difficult to find a clear distinction between 'strong sustainable' and 'weak sustainable' as well as to distinguish between the conceptions of 'younger men' and 'older men' in daily life.
(2) For both qualitative and quantitative BSIs, people are difficult to determine the sustainability degree corresponding to a given system performance information. The relation between system performances parameters and indicators value is, in turn, fuzzy and different to the physical relation between two physical quantities. When people give a judgment on the sustainability degree of someone qualitative BSIs, it is difficult to model the uncertainty in human judgement.
(3) The two types of fuzziness and/or uncertainties discussed above are also existing in the determination of BSI weights. For example, in the step of pair-wise comparison in AHP, the human preference of each pair of BSIs is difficult to define.

To sum up, all the problems are caused by the uncertainties of human awareness or the complex definition of sustainability. To solve the uncertainties, fuzzy sets theory is needed to combine with the BSIs' quantification and GSI's aggregation. A framework of the development of GSI based on fuzzy sets theory is proposed below.

5. Proposed framework of the development of GSI

5.1. Overview of the proposed framework

In order to deal with the shortcomings and challenges discussed above, the five strategies shown in the flow chart (Fig. 2) is detailed in the framework shown in Fig. 5. In the first strategy ((A) BSIs selection), it is necessary to identify the sustainability assessment criteria and then select BSIs for GSI development. The linear normalization method is used in the second strategy ((B) BSIs normalization). The fuzzy comprehensive evaluation is employed as the methodology of the third strategy ((C) BSIs evaluation), which includes fuzzification, construction of assessment set, building of judgment vector, establishment of evaluation matrix and defining of evaluation algorithm. The fourth strategy ((D) BSIs weighting) uses fuzzy AHP to determine the weights of all the BSIs. This includes pair-wise comparison of BSIs, weights calculation, consistency validation and weight vector determination. Finally, the weighted arithmetic mean method is used in the fifth strategy ((E) GSI aggregation) to aggregate the GSI and calculate the final numerical result of GSI.

5.2. Selection of BSIs

Eleven BSIs are selected for the GSI development based on TBLs approach including the three sustainable considerations: environmental, economic and social.

5.2.1. Environmental indicators

Environmental indicators have to reflect the impacts of an RES on environmental sustainability. These types of indicators consider GHSs emissions, energy balance analysis, and energy efficiency.

5.2.1.1. CO_2 emission. Carbon dioxide (CO_2) is one of the typical greenhouse gases (GHGs) defined by the Kyoto Protocol [55]. It was reported that CO_2 contributes 9–26% to the global warming [18,56]. This gas is mainly released through the combustion of coal/lignite, oil and natural gas in energy systems. A hybrid renewable energy system including a grid component or diesel electricity generator as backup system has CO_2 emissions. Different systems have different CO_2 emission factors. Moreover, the processes of the manufacture, installation and scrapping of system's components have also CO_2 emissions of the system's whole life cycle. CO_2 emissions of RES are definitely used as an important indicator to assess system sustainability [3,7,16,25,37,38,57–66].

5.2.1.2. NO_x emission. Nitrogen oxides (NO_x) is a generic term for mono-nitrogen oxides (mainly NO and NO_2) which are also typical GHGs [55]. The burning of biomass fuel and traditional fuel as petroleum and coal causes NO_x emissions [67]. This type of emission comprises a group of gas molecules that contribute to local air pollution, acid deposition and global climate change. The majority of literatures about NO_x emissions are relative to the sustainability assessment of RES, and NO_x emission is an significant indicator for the sustainability assessment of an energy system [3,7,16,25,37,38,57–59,64,66].

5.2.1.3. SO_2 emission. Sulfur dioxide (SO_2) is a colorless gas or liquid with a strong, choking odor. It is produced from the combustion of fossil fuels (like coal and petroleum) and the smelting of mineral ores (aluminum, copper, zinc, lead and iron) that contain sulfur, and therefore the non-renewable energy components and embodied energy and materials in renewable energy devices have this type of emission. SO_2 exposure can also be a threat to people and animal health problems. In the terms of environmental impacts, SO_2 emission is a precursor to acid rain and atmospheric particulate [68] and in turn to climate change. This type of emission is used as an important sustainability indicators of energy system [3,7,16,25,37,38,57,58].

5.2.1.4. Renewable fraction. Renewable fraction is the proportion of different renewable energy sources in a system. There are few literatures which used renewable fraction as an indicator [69], but some papers discussed this parameter individually in sustainability assessment of a RES, especially a hybrid RES [70–72].

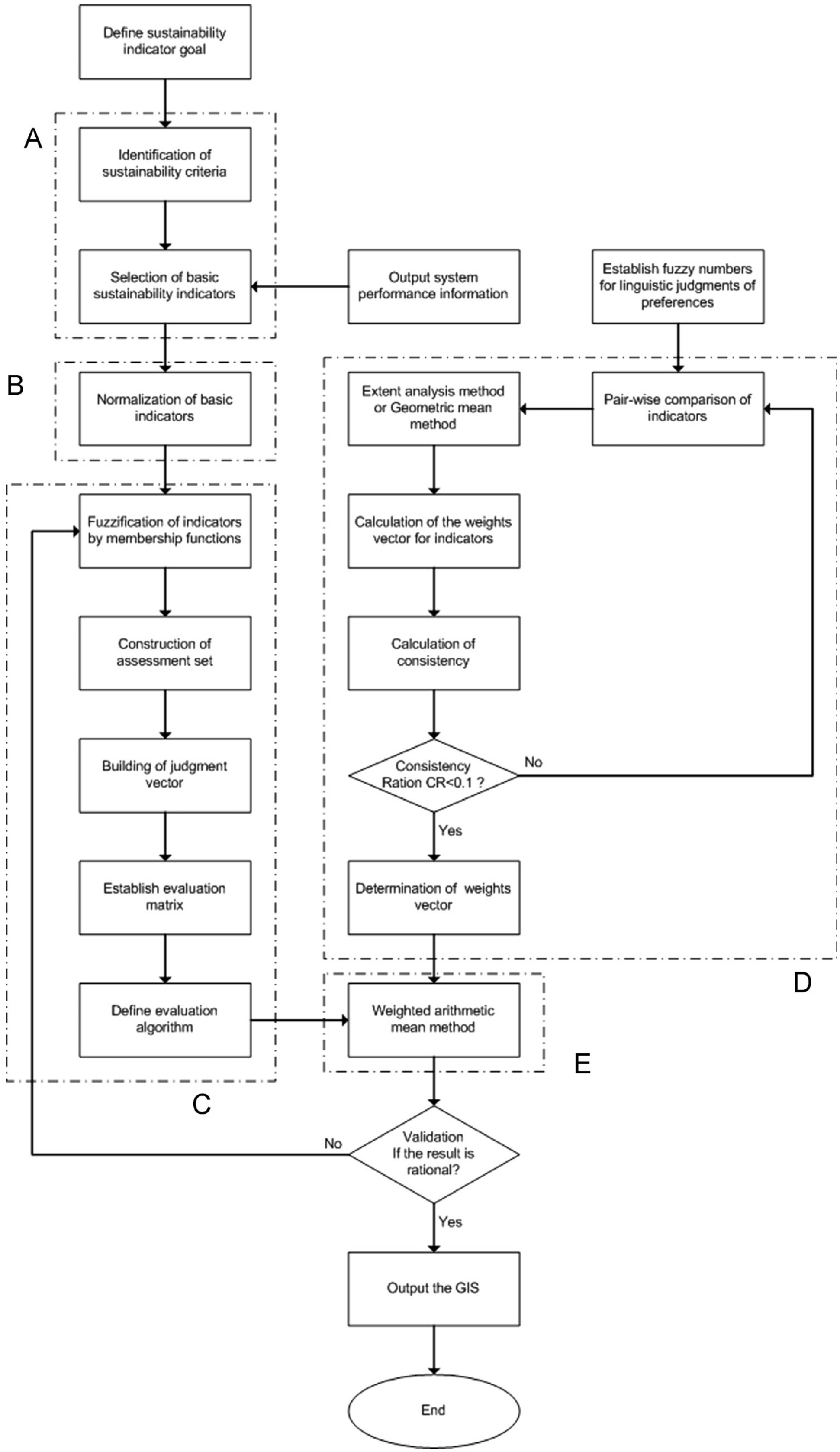

Fig. 5. The framework of GSI development.

5.2.1.5. Energy efficiency. Energy conservation requires efficient use of energy [73]. Energy efficiency is defined as the ratio between the useful output of an energy conversion machine and the input. A number of literatures adapted energy efficiency as sustainability indicator [3,16,23,25,57–59,74–78]. Sometimes, the indicator of energy efficiency is replaced by exergy efficiency,

energy consumption per person (per capita or per year) [73] or energy consumption per dollar of gross domestic product [73]. In some previous studies, exergy efficiency was used as an individual indicator of sustainability assessment [79–81].

5.2.2. Economic indicators

Economic indicators are needed to assess the economic effect on the evaluation of RES. In general, costs and return analysis, and payback period are used frequently.

5.2.2.1. Costs. Costs of a RES are the primary considerations of a sustainability indicator. A RES mainly includes three parts of costs: capital cost, replacement cost and operation and maintenance (O&M) cost [82]. In order to assess the whole system comprehensively, these three types of costs are calculated by two indicators: cost of energy (COE) and net present cost (NPC). The COE, which is defined as the cost of per kWh electricity, is widely used as a sustainability indicator [3,16,58,61,65,83–85]. The NPC representing the sum of the present value of all costs of the system is also applied as sustainability indicator [86–89].

5.2.2.2. Return on investment. Return on investment (ROI), in finance, measures the internal rate of return earned by the existing projects of a firm [90]. The ROI of a RES refers to the internal rate of return earned by the system. There are four inputs of ROI namely gross investment, gross cash flow, expected life of the assets, and expected value of the assets. Because of the investors considerations about cash flow of systems, some RES simulation softwares are able to give the solutions methods of ROI calculations, like HOMER software produced by the National Renewable Energy Laboratory (NREL) of USA [82].

5.2.2.3. Payback. Payback time is a measure of how quickly cash flows are generated by the system to cover the initial investment [90]. Investors obviously prefer a shorter payback time to a longer payback time. The financial term is used as a sustainability indicator of RES [46,75,91], and this had been reviewed by Wang [18]. In life cycle assessment (LCA) of energy system, payback is extended to energy payback time (EPBT) and GHG payback time (GHGPBT) which are used as intensity indicators. For example, the literature [92] uses EPBT and GHGPBT evaluating energy environmental impacts of a wind turbine; and the literature [93] employed cost payback time (CPBT) and EPBT to assess the sustainability of a solar system. In this paper, payback time is used as a basic economic indicator.

5.2.3. Social indicators

Social indicators consider the social impacts of a RES. Generally, job creation, benefited residents and others are adopted.

5.2.3.1. Job creation. During the whole life cycle of a RES, it creates direct or indirect jobs for people. This helps to improve the living quality of the local people [94]. In the sustainability indicator development process, job creation is selected by many literatures [11,25,32,58,75]. Especially, it is pointed out that the determinations of job creation are the number of hours of a new job to be opened corresponding to the respective option in the following 10 years [4].

5.2.3.2. Benefited residents. The indicator of benefited residents measures how much residents have benefitted from the RES [95–97]. It is also derived by benefited areas that refers to the number of m^2 per unit power [4].

5.3. Fuzzy analytical hierarchy process (FAHP)

In order to deal with the vagueness or imprecision of human cognitive processes in the development of GSI, the AHP method is combined with the fuzzy sets theory. In the FAHP, users are necessary to state whether he/she is indifferent to the two attributes or whether he/she has a weak, strict, strong, or very strong preference for one of the BSIs. Therefore, the nine-point intensity scale for pair-wise comparison is generally suggested to express the degrees of preference between the two elements [98]. A set of sustainability judgements can be used to compare the preferences: 'equally preferred/important', 'moderately more preferred/important', 'strongly more preferred/important', 'very strongly more preferred/important' and 'extremely more preferred/important' [31,99]. As shown in Table 4, each membership function is expressed by triangular fuzzy number, the left point (l), the middle point (m) and right point (u).

The following step of FAHP is to make a pair-wise comparisons of alternatives with respect to attributes in a matrix ($\underset{\sim}{A}$).

$$\underset{\sim}{A}=\begin{bmatrix} \underset{\sim}{a}_{11} & \underset{\sim}{a}_{12} & \cdots & \underset{\sim}{a}_{1n} \\ \underset{\sim}{a}_{21} & \underset{\sim}{a}_{22} & \cdots & \underset{\sim}{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \underset{\sim}{a}_{n1} & \underset{\sim}{a}_{n2} & \cdots & \underset{\sim}{a}_{nn} \end{bmatrix}=\begin{bmatrix} 1 & \underset{\sim}{a}_{12} & \cdots & \underset{\sim}{a}_{1n} \\ \underset{\sim}{a}_{21}^{-1} & 1 & \cdots & \underset{\sim}{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \underset{\sim}{a}_{11}^{-1} & \underset{\sim}{a}_{2n}^{-1} & \cdots & 1 \end{bmatrix} \tag{18}$$

where

$$\underset{\sim}{a}_{ij}=\begin{cases} \underset{\sim}{9}^{-1},\ \underset{\sim}{7}^{-1},\ \ldots,\ \underset{\sim}{1}^{-1},\ \underset{\sim}{1},\ \underset{\sim}{3},\ \ldots,\ \underset{\sim}{9}, & i\neq j \\ 1, & i=j \end{cases}.$$

Because each self-comparison of preference is equal to 1 and equivalent cells are reciprocal, we know that $\underset{\sim}{a}_{ij}=\underset{\sim}{a}_{ji}^{-1}$.

After this matrix is established, a vector of weights can be computed. The extent analysis of triangular fuzzy number is based on Chang's method [100]. In addition, the consistency ratio is used to validate the results of FAHP. Similar to the crisp AHP method, the GMM is also used in finalizing the weighting process [28].

5.4. Fuzzy comprehensive evaluation

The fuzzy method is employed to integrate all the BSIs into GSIs. This method can be carried out by the following five steps: determination of assessment set, determination of judgment set, development of evaluation matrix, determination of evaluation algorithm, and processing evaluation indicator.

5.4.1. Fuzzification

The fuzzification is the process of transforming crisp numbers into grades of membership for linguistic terms of fuzzy sets. It uses membership function to associate a grade to each linguistic term.

Table 4
Membership function of fuzzy number for linguistic variables of preference.

Scale	Description	FN[a]	MF[b]
1	Equally important or preferred	$\underset{\sim}{1}$	(1, 1, 3)[c]
3	Moderately more important/preferred	$\underset{\sim}{3}$	(2, 3, 4)
5	Strongly more important/preferred	$\underset{\sim}{5}$	(4, 5, 6)
7	Very strongly more important/preferred	$\underset{\sim}{7}$	(6, 7, 8)
9	Extremely more important/preferred	$\underset{\sim}{9}$	(8, 9, 10)

[a] FN means fuzzy number.
[b] MF means membership function, given by (l, m, u).
[c] For self-comparison, the MF is changed to nonfuzzy number 1 (1, 1, 1).

Table 5
Fuzzy number for linguistic variables for the rating of sustainability evaluation.

Linguistic scales	Corresponding TFN
Very weak sustainable	(0, 1, 3)
Weak sustainable	(1, 3, 5)
Fair sustainable	(3, 5, 7)
Strong sustainable	(5, 7, 9)
Very strong sustainable	(7, 9, 10)

For the variety of sustainability value, more types of sustainability scales are coming in academic fields as shown in Section 3.2. For BSIs, the five-degree scale fuzzy sustainability indicator is borrowed from Sun's paper [101]. The linguistic variables and corresponding fuzzy sets are very poor ($\underset{\sim}{1} = [0,1,3]$), poor ($\underset{\sim}{3} = [1,3,5]$), fair ($\underset{\sim}{5} = [3,5,7]$), good ($\underset{\sim}{7} = [5,7,9]$) and very good ($\underset{\sim}{9} = [7,9,10]$).

5.4.2. Determining assessment set

Determining an assessment set is to determine a vector with m types of criterion to describe sustainability. The vector is noted by

$$U = \{u_i | i = 1, 2, \ldots, m\} \tag{19}$$

where u_i represents the i-th criterion of sustainability.

5.4.3. Determining judgment set

As a basic character of fuzzy logic, there is no accurate description but linguistic variables for evaluating each criterion. A vector of the linguistic variables is defined by

$$V = \{v_j | j = 1, 2, \ldots, n\} \tag{20}$$

where v_j represents the j-th linguistic evaluation of BSIs.

The value of v_{ij} are fuzzified by the following equations: Eq. (21) for positive indicators and Eq. (22) for negative indicators:

$$d_{ij,\ pos.}(x_j) = \begin{cases} 0, & x_j \le x_{min(i)} \\ \dfrac{x_j - x_{min(i)}}{x_{max(i)} - x_{min(i)}}, & x_{min(i)} < x_j \le x_{max(i)} \\ 1, & x_j > x_{max(i)} \end{cases} \tag{21}$$

and

$$d_{ij,\ neg.}(x_j) = \begin{cases} 1, & x_j \le x_{min(i)} \\ \dfrac{x_{max(i)} - x_j}{x_{max(i)} - x_{min(i)}}, & x_{min(i)} < x_j \le x_{max(i)} \\ 0, & x_j > x_{max(i)} \end{cases} \tag{22}$$

where $d_{ij,\ pos.}(x)$ represents the positive indicator, such as renewable fraction and conversion efficiency; and $d_{ij,\ neg.}(x)$ represents the negative indicator, such as cost of energy and CO_2 emissions.

For each judgments of all the fuzzified indicators, Eq. (23) is used to determine the fuzzy evaluation matrix $R = \{r_{ij}\}$:

$$r_{ij}(d_{ij}) = \begin{cases} 0, & d_{ij} < a \quad \text{or } d_{ij} \ge c \\ \dfrac{d_{ij} - a}{b - a}, & a < d_{ij} \le b \\ \dfrac{d_{ij} - b}{c - b}, & b < d_{ij} \le c \end{cases} \tag{23}$$

where a, b and c are respectively the left, medium and right points of a triangle fuzzy number.

5.4.4. Constructing evaluation matrix

According to all the criteria and BSIs mentioned above, the sustainability evaluation based on some on single criterion can be assessed relatively easier. The assessment matrix including all the BSI can be combined with an evaluation matrix which is given by

$$R = \{r_{ij}\} = \begin{array}{c} \\ u_1 \\ u_2 \\ \vdots \\ u_m \end{array} \begin{array}{c} \begin{array}{cccc} v_1 & v_2 & \ldots & v_n \end{array} \\ \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \end{array} \tag{24}$$

here r_{ij} means the membership of the j-th linguistic evaluation v_j with a view to the i-th criterion u_i. The elements R_{ij} in R are crisp numbers. They are similar to the values of v_{ij} from Table 5: very weak sustainable, weak sustainable, fair sustainable, strong sustainable and very strong sustainable.

5.4.5. Building evaluation algorithm

The evaluation model can be implemented by

$$B' = W \times R \tag{25}$$

where W is the weight vector presenting the weights of all the BSIs. Here, a multiplication cross operation is used to calculate the evaluation model, and the calculated results vector $B' = \{b'_i \mid i = 1,\ 2,\ \ldots,\ m\}$ represents the evaluation vector. After that, a normalization is used again to calculate the scores by the value in the interval [0,1].

6. Conclusion

A framework of the development of general sustainability indicator for RESs is constructed in this paper by discussing the concepts of SI, reviewing different sustainability assessment criteria and scales, and comparing the previous methods of BSIs quantification and GSI modeling.

It is found that the discrete scale of sustainability assessment (e.g. 3-degree scale, 9-degree scale) is unable to measure sustainability precisely. It is also found that traditional and crisp data analysis methods are difficult to indicate the concepts of sustainability and difficult to present the fuzzy judgment of GSI users. Fuzzy sets theory is, therefore, incorporated in the multi-criteria decision-making method AHP in the framework.

The detailed methods of the five strategies of the framework of GSI development are introduced finally. First, the TBL approach is used in the strategy A (BSIs selection). It is concluded that the most popular BSI is the CO_2 emission indicator of environmental criteria. In the economic consideration, costs indicator is widely used to analyze the system quality. A lower value of cost means better. There are two common social indicators: job creation and the number of residents benefited. Second, the linear normalization method is used in strategy B (BSIs normalization), and the fuzzy comprehensive evaluation is employed in the strategy C (BSIs assessment). The fourth strategy D (BSIs weighting) uses fuzzy AHP method to determine BSIs weights. Finally, the weighted arithmetic mean method is used in the strategy E (GSI aggregation) to aggregate the GSI and calculate the final numerical result of GSI.

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